MOVEMENT OF TRACERS THROUGH SOIL

By

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Preface

by

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This study, carried out at the Ministry of the Environment Experimental Facility at Whitby, Ontario, was designed to investigate the use of tracers for determining movement of ground water, specifically that into which contaminants may have been introduced by subsurface disposal of sewage effluents.

The results of the study indicate that tritium is an excellent tracer material but requires special care in its use due to its radioactivity. The use of tritium requires approval by the Atomic Energy Control Board. Fluorescein is an acceptable tracer in sand but not in soil containing clay and silt.

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1. Introduction

Increased concern of the public for preserving the high quality of lake waters as well as the constant efforts of sanitary engineers directed at reducing contamination of lake waters caused by individual sewage disposal systems brought about studies on underground movement of pollutants from disposal systems towards lakes. (1,2,3,4).

In order to study the movement of ground water, which is the vehicle transporting the pollutants, proper tracers are required which, when mixed with the pollutants, move towards the lake with the same velocity as the ground water and which are not fixed in the soil.

The soil characteristics, the distance of the sewage disposal system from the receiving waters and the time the chemical and bacteriological pollutants are in contact with the soil and ground water are considered to be the most important factors determining the quality of the treated effluent before it enters the receiving waters. The degree of aeration of the soil which sometimes is affected by high water table or by impervious cover over the leaching area is also considered to be of great importance in removal of contaminants by soil.

In cases where the ground water surface is very close to ground surface or in cases where only a thin layer of soil is spread on bed rock, raised sand filters have been built on the ground surface in order to obtain adequate treatment of septic tank effluent.

The purpose of this study was to select a proper tracer for studying the underground movement of spetic tank effluent and to determine the velocity of the ground water movement when the soil conditions and the gradient of water table were known.

It was also the intention of this study to determine the velocity of movement of radioactive and dye tracers through sand filters where sands of different grain sizes and different uniformity coefficients were used.

The movement of tracers through sand filters was studied in 1971 at the Whitby Experimental Station; the movement of tracers through natural soil was studied in 1972-74 by using the lot adjacent to the same station.

2. Method and Techniques

In normal soil absorption sewage disposal systems, domestic sewage, after passing through a primary process of settling and bio-degradation in the septic tank, enters the absorption trenches of the tile field and then moves vertically towards the ground water, usually passing through about one metre of unsaturated soil between the bottom of the trench and the water table. The further movement of the effluent is with the ground water.

In order to create flow conditions similar to those existing in a normally working soil absorption system two methods were applied for studying the movement of tracers through soil:

1. Tracers were introduced into a shallow hole drilled in the ground to a depth of about one metre above the water table (Fig. 1). Such a hole is called in this report "blind hole" in order to distinguish it from the other (sampling) holes called "well points". The well points were located downstream from the blind hole and drilled in the ground to a depth of about 0.5 metres below the water table. The well points were cased with 75 mm unperforated pipes, the lower end of which had three or four slits cut, each 5 mm wide and about 0.5 m in length, to facilitate entry of ground water to the cased well point. The "blind hole" and well points 1 and 2 were located on a line parallel to the direction of ground water flow; well points I, II, III, and IV (dashed lines on Fig. 1) were also located downstream from the blind hole but not on the same direction line as well points 1 and 2. In this part of the experimental

study the tracers moved initially vertically through a one metre layer of unsaturated soil and then, with the ground water, downstream towards the well points where they were picked up in the water samples tested for concentration of tracers, and phosphorus. The "blind hole" method which simulates, to some extend, the flow of septic tank effluent from absorption trenches to the ground water, was applied in studying the movement of tracers in soil during the 1972 part of this study.

2. Tracers were introduced directly into the ground water through a well point drilled to a depth of 0.5 m below the water table. The well point was cased with a 75 mm unperforated plastic pipe having slits at the lower end to facilitate ground water movement (Fig. 2). The tracers then moved downstream with the ground water in the saturated part of the soil only and the velocity of their movement was determined more accurately than in the case where a "blind hole" was used. This method was applied in 1974-75 part of this study.

Before the blind hole and the well points were located the direction of the ground water movement was determined by using the "three point method". The method is based on an assumption that the water table, within a limited area, is a sloping flat plane and that the ground water moves mostly in the direction of the maximum slope of the plane.

Assuming that the levels of the water table in three well points A,B,C, which are not located on one straight line, are "a",

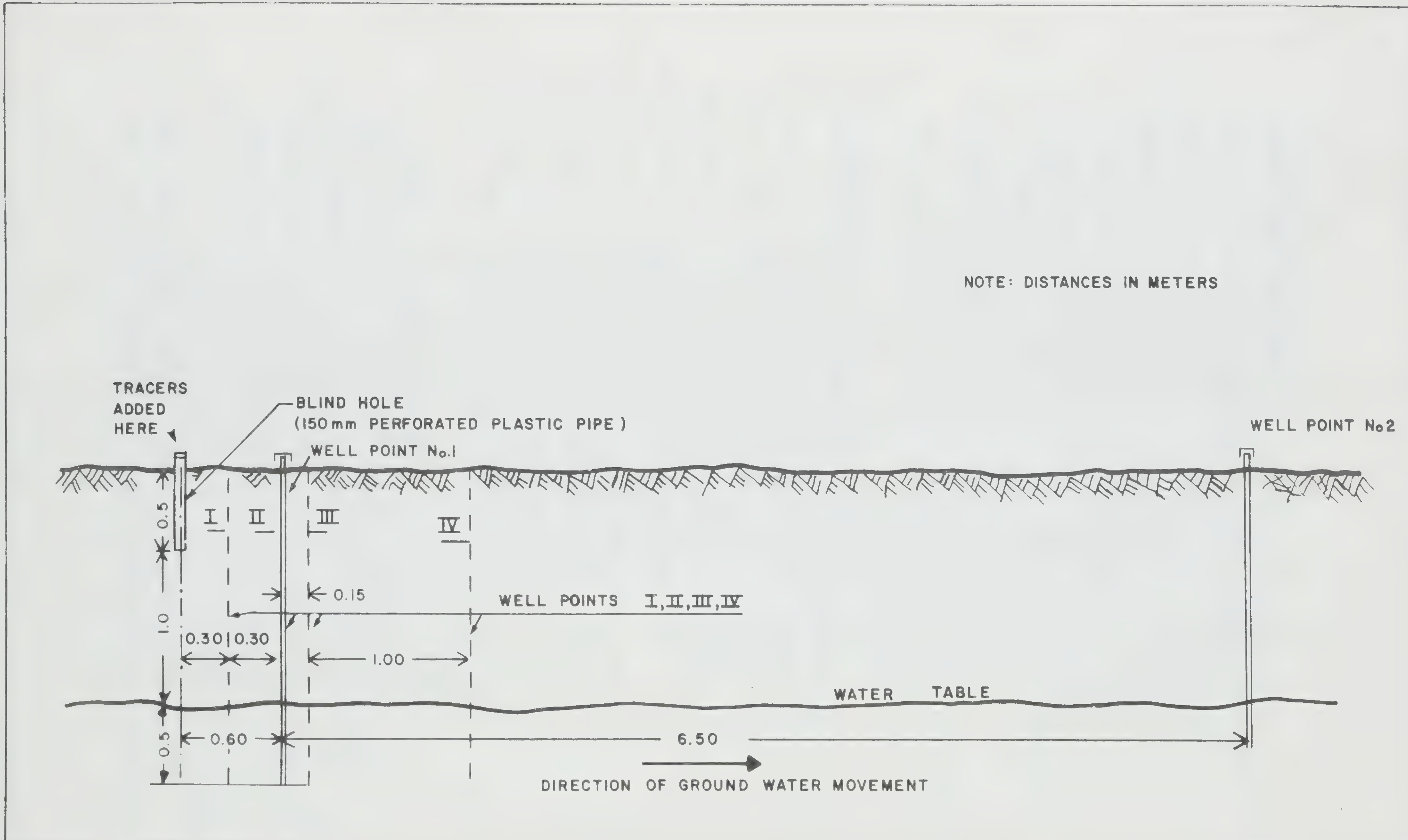

FIG.1 GROUND PROFILE AND LOCATION OF WELL POINTS (1972 STUDY).

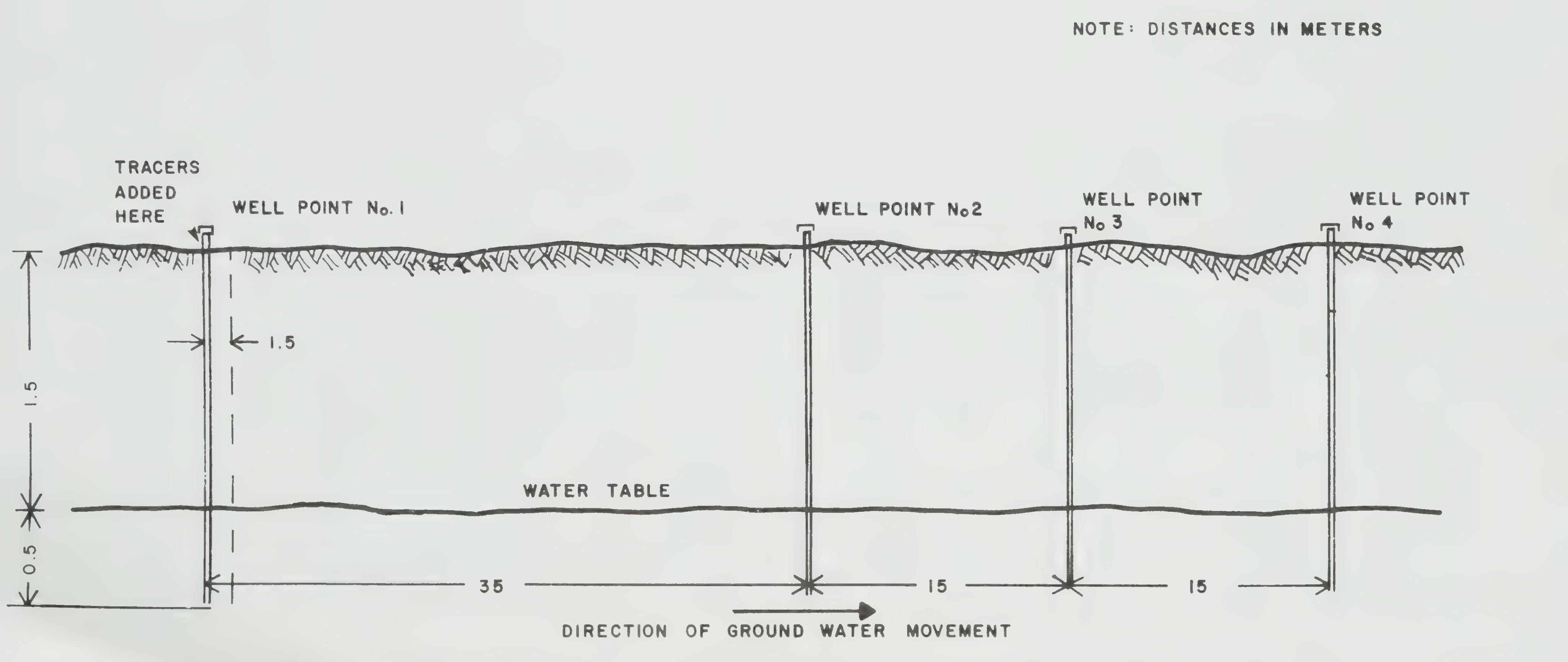

FIG. 2 GROUND PROFILE AND LOCATION OF WELL POINTS (1974 STUDY).

"b" and "c" cms. where a > b > c (Fig. 3). There must be one well point D on the line A-C in which the level of the water table is equal to "b". Any line perpendicular to B-D drawn from a point of a higher level than "b" shows the direction of maximum slope and the direction of the fastest ground water flow.

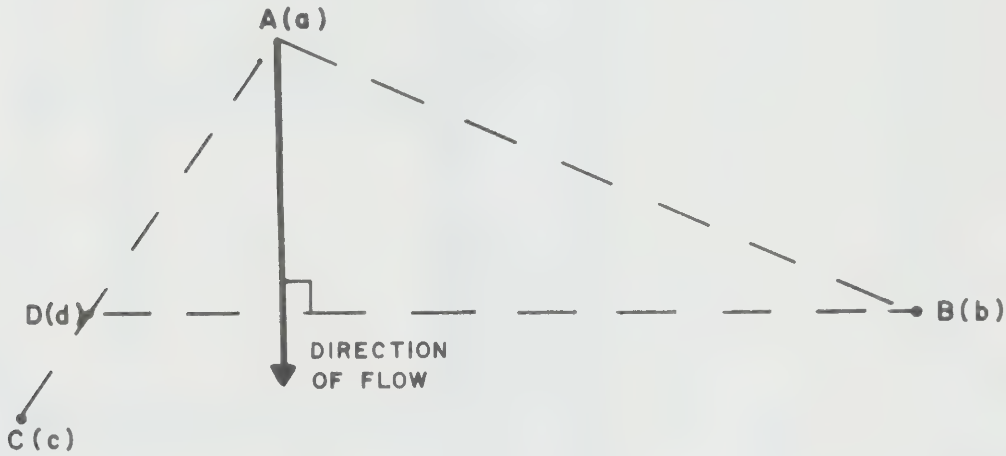

Fig. 3 "Three point method" of determination of direction of ground water movement.

3. The velocity of movement of tracers through sand filters was determined by adding tracers to the septic tank effluent before it entered the filters and then measuring the time taken by the tracers to pass through the filters of a known thickness. The construction and the dimensions of the sand filters as well as the method the filters were loaded with septic tank effluent was described in detail in earlier publications.(5, 6).

3. Tracers Used

According to some earlier studies tritium was found to be a nearly "ideal ground water tracer" (2, 7, 8, 9) which moves through soil at the same velocity as the ground water (2, 10) showing low absorptive loss to the soil (11) and good detectability in low concentrations.

Fluorescein was not found to be a suitable tracer for tracing the movement of septic tank effluent in uniform undisturbed soil containing clay and silt (4). Fluorescein moves freely only in media of high permeability (3).

a) In the 1972 part of this study two tracers were used: tritium and fluorescein. The concentrations of the tracers were: 40 millicurie of tritium diluted in one litre of water (40 mCi/l) and 200 g of fluorescein disolved in one litre of water (200 g/l). The tracers were introduced into the blind hole on May 30, 1972 (see Fig. 1). In addition to the tracers, 2 litres of potassium dihydrogen phosphate (KH_2PO_4) of a concentration of 28.5 g/l (as P) were introduced into the same blind hole in order to observe, at the same time, the movement of phosphorus through soil.

Before introducing the tracers and the phosphate into the blind hole, daily background ground water samples were taken from the well points for 12 consecutive days. The sampling was continued, after the tracers and phosphate were introduced, until July 12, 1972. The water samples were tested for tritium, fluorescein and phosphorus concentrations.

b) In the 1974 part of this study the same kind of tracers and chemical were used as in 1972, but the radioactivity of the tritium

used was higher and the concentrations of fluorescein and phosphorus were different than in 1972. One hundred millicuries of tritium, 10 grams of fluorescein and 17 grams of potassium dihydrogen phosphate (KH_2PO_4) each of them diluted in one litre of water, were introduced on August 19, 1974 directly into the ground water (Fig. 2). The tracers and the phosphate were then pushed downstream with the ground water by pouring 5 litres of water into the same hole.

Before the tracers and phosphate were introduced background water samples were taken from the well points for 5 days and tested for tritium, fluorescein and phosphorus concentrations.

c) When studying the vertical velocity of movement of tracers through sand filters (1971) the following tracers were added to the septic tank effluent: 40 mCi of tritium, 200 g of fluorescein and 200 g of rhodamine B.

4. Soil Characteristics

The Whitby Testing Site is underlain by a deposit of clayey silt till of glacial origin. The soil stratigraphy consists of 0.1 to 0.2 metres of top soil which is dark brown in colour and contains grass roots and organic matter. Below the layer of top soil, the clayey silt till contains small pores (probably worm holes) and very fine cracks and extends to a depth of about 1 m. The brown clayey silt below has a small amount of fine gravel particles in the soil and in some areas at the testing site, at the depth of approximately 1.5 m, there is a larger amount of gravel particles mixed in the clayey soil. At the time of the field investigation the soil profile was determined to the depth of about 3.5 m; however, it is believed that the clayey till extends to a greater depth.

Soil samples were taken from a number of points at the testing site for laboratory testing, which included the determination of the grain size distribution, the plasticity and the coefficient of permeability of the soil.

The soil test results are summarized as follows:

(a) Grain Size Distribution*

Sand (2.0 - 0.075 mm) ....6% to 25%
Silt (0.075 - 0.002 mm).........44% to 45%
Clay ($<$0.002 mm) ....30% to 50%

(b) Plasticity

liquid limit....................33.4%
Plastic limit...................17.1%
Plasticity index................16.3%

(c) Laboratory Coefficient of Permeability - K_l

..........0.9×10^{-7} cm/sec

The coefficient was measured in a triaxial-permeameter as described by Chan and Kenney (12) on a 5-cm diameter Shelby tube soil sample. The constant-head method was used for the measurement.

(d) Field Coefficient of Permeability - K_f

............0.5×10^{-7} cm/sec

The coefficient was measured at two locations at the testing site with a driven-type piezometer. The method suggested by Wilkinson (13) was used.

*The Unified Soil Classification System is used.

(e) Percolation Test Results

A number of percolation tests were performed at the testing site at a depth of about 0.6 m. The percolation time varied from 2 to 10 minutes/cm. (5-25 min/inch).

5. Results obtained

5.1 Movement of Tritium through soil

The tritium which was introduced into the blind hole on May 30, 1972 was detected on June 23, 1972, i.e. 24 days later, in well point 1, located at a distance of 0.6 metres from the blind hole (Fig. 1). During the next 13 days (between June 23 and July 6, 1972) the tritium moved an additional distance of 6.5 m in the same direction (downstream) to reach well point 2.

The horizontal speed of movement of tritium within the saturated zone, presumably the same speed as that of the ground water, was 0.50 m/day. According to Corey et al (2) the velocity of tritium used as a tracer of water movement in Kaolinitic soil, is almost the same as that of the water itself. The calculated speed of the vertical movement of tritium in the unsaturated 1.0 m layer of soil, between the bottom of the blind hole and the water table, was 0.04 m/day.

On August 19, 1974 the tritium was introduced directly into the ground water (well point #1, Fig. 2), and was detected 63 days later (Oct. 21, 1974) in well point #2, and 106 days after injection (i.e. on Dec. 3, 1974) in well point #4.

The distance between well points 1 and 2 was 35 m and between 2 and 4, 30 m (Fig. 2). The calculated speed of the underground movement of the tritium between well points 1 and 2 was 0.56 m/day and between 2 and 4, 0.70 m/day.

The average speed of the underground movement of tritium between points 1 and 4, presumably the same speed as that of the ground water, was 0.61 m/day.

On Dec. 3, 1974 tritium was also found in the ground water of well point #3 located at a distance of 50 metres from well point #1. However, the concentration of tritium in that well point was already very high when detected (114,000 nCi/l) and almost the same as the peak concentration of tritium observed in well point #3 several days before Dec. 3, 1974, thus the speed of underground movement must have been greater than 0.47 m/day.

The above results on movement of tritium are summarized in Table 1.

Table 1 Movement of Tritium through Soil

Source of tracer and direction of movement	Distances (in metres)		Time of movement (from source of tracer to well point) (days)	Average velocity of movement (m/day)
	Vertical (from bottom of blind hole to ground water)	Horizontal (from source of tracer to well point)		
1972 study (see Fig. 1)				
Blind hole to well point 1	1.0	0.6	24	0.07
well point 1 to well point 2	-	6.5	13	0.50
1974 study (see Fig. 2)				
well point 1 to well point 2	-	35.0	63	0.56
well point 2 to well point 4	-	30.0	43	0.70
well point 1 to well point 4	-	65.0	106	0.61

The average speed of underground movement of tritium with the ground water observed in the 1974 study (0.61 m/day) was approximately 22% greater than that observed in the 1972 study (0.50 m/day). The difference in speed can be attributed only to the higher hydraulic gradient of the water table (4% in 1974 and 1% in 1972 study) because the soil conditions were the same.

It was observed that the concentration of tritium, at a given point in the ground water, changes with time and follows closely Gumbel's standard skewed distribution curve which characterizes most hydrologic phenomena (14). After the tritium is first detected in the ground water the concentration of tritium rises rapidly to a peak point and then decreases gradually during a longer period of time (Fig. 4).

5.2 Movement of Fluorescein through Soil

The fluorescein introduced into the blind hole (Fig. 1) during the 1972 study, was not detected in well point #1 located at a distance of only 0.6 m from the blind hole. All of the fluorescein introduced into the blind hole apparently was fixed in the undisturbed clayey soil.

When fluorescein was introduced directly into the ground water (well point #1, Fig. 2, 1974 study) it was not detected in the ground water at a distance of 1.5 metres.

5.3 Movement of Phosphorus through Soil

The speed of movement of phosphorus in soil and the distance the phosphorus is able to move through soil, were investigated during the 1972 part of this study. Water samples for phosphorus concentration tests were taken periodically from well points located at different

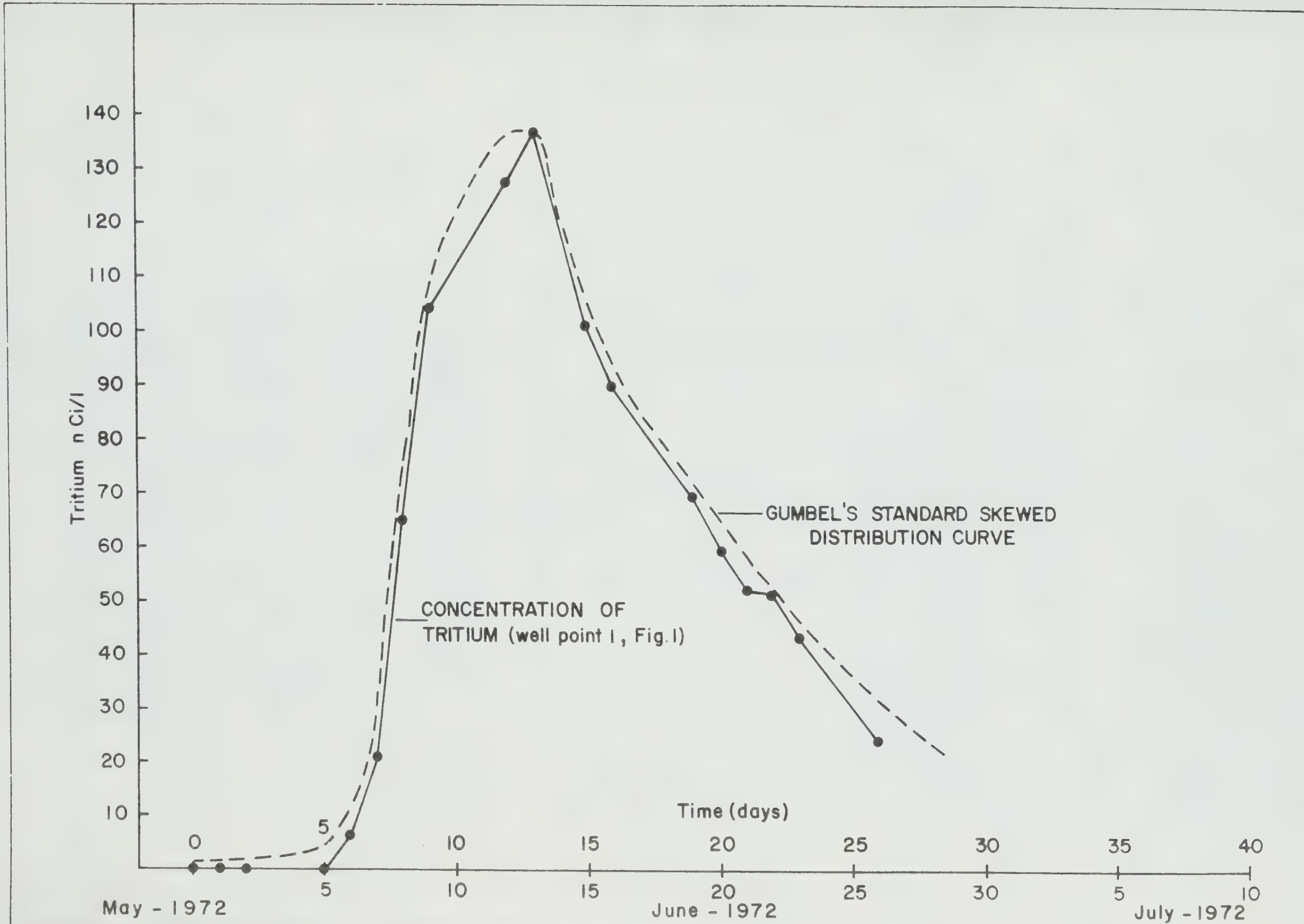

FIG. 4. EFFECT OF TIME ON CONCENTRATION OF TRITIUM IN GROUND WATER. (1972 STUDY)

distances downstream from blind hole. Table 2 shows the horizontal distances of well points from the blind hole, the combined time of movement of the phosphorus in the vertical (unsaturated) and horizontal (saturated) portions of soil and the calculated average speed of movement.

Table 2 Movement of Phosphorus through Soil
(1972 Study)

Sample Source (see Fig. 1)	Distances (in metres)			Time of Movement from blind hole (days)	Average Speed of Movement (m/day)
	From bottom of blind hole to ground water (vertical)	From blind hole to well point (horizontal)	Total		
Well point I	1.0	0.30	1.30	20	0.07
Well point II	1.0	0.60	1.60	24	0.07
Well point III	1.0	0.75	1.75	20?	0.09
Well point IV	1.0	1.75	2.75	46	0.06

The maximum distance from the blind hole reached by the phosphorus moving through soil was 1.75 metres. The average speed of movement of the phosphorus in soil (unsaturated and saturated) was 0.07 m/day, i.e. of about ten times lower than that of the underground movement of tritium which is considered to move with the same velocity as water (2).

The relatively slow movement of the phosphorus in soil and the observed short range of movement can be attributed only to the phenomenon of phosphorus retention in soil.

In the 1974 part of this study, phosphorus in the form of a KH_2PO_4 solution was introduced directly into the ground water. No

increase in concentration of phosphorus in the ground water was observed at a distance of 1.50 m downstream from the injection point. The velocity of phosphorus movement was not determined during the 1974 study.

5.4 Vertical Movement of Tritium and Fluorescein through Sand Filters

As was anticipated, the velocity of movement of the tracers through the sand filters was greatly affected by the grain size of the sand; in fine sand the velocity was lower than in coarse. About 7.0 m/day was the vertical velocity when sand of a grain size of D_{10} = 0.24 mm and uniformity coefficient C_u = 2.8 was used, and as great as about 17.0 m/day in sand of D_{10} = 2.5 mm and C_u = 1.2. The velocity of movement of tritium in sand was not greater than the velocities of the dye tracer, as distinguished from velocities observed in undisturbed soil where the tritium moved faster than other tracers. The sand characteristics and the determined vertical velocities of movement of the tracers are shown in Table 3.

Table 3 Sand Characteristics and Vertical Velocities of Tracers in Sand

	Sand Filter* #	1	2	3	5	6
Sand Characteristics	Grain Size D_{10} mm	0.24	0.30	0.60	1.0	2.5
	Uniformity Coefficient C_u	2.8	4.1	2.7	2.1	1.2
Velocities in Sand	Velocity of Tritium (m/day)	7.1	7.1	11.0	4.9?	16.8
	Velocity of Fluorescein & Rhodamine (m/day)	7.1	7.1	11.0	11.0	16.8

* Sand Filter No. 4 was not used in this study.

The pattern of the effect of time on concentration of tracers in final effluent from the sand filters was again similar to that observed at a given point in the ground water downstream from the tracer injection point. Figures 5 and 6 show the concentrations of tritium and fluorescein in the final effluent from sand filters 3 and 6. The concentrations of Rhodamine B in the effluent followed the same pattern.

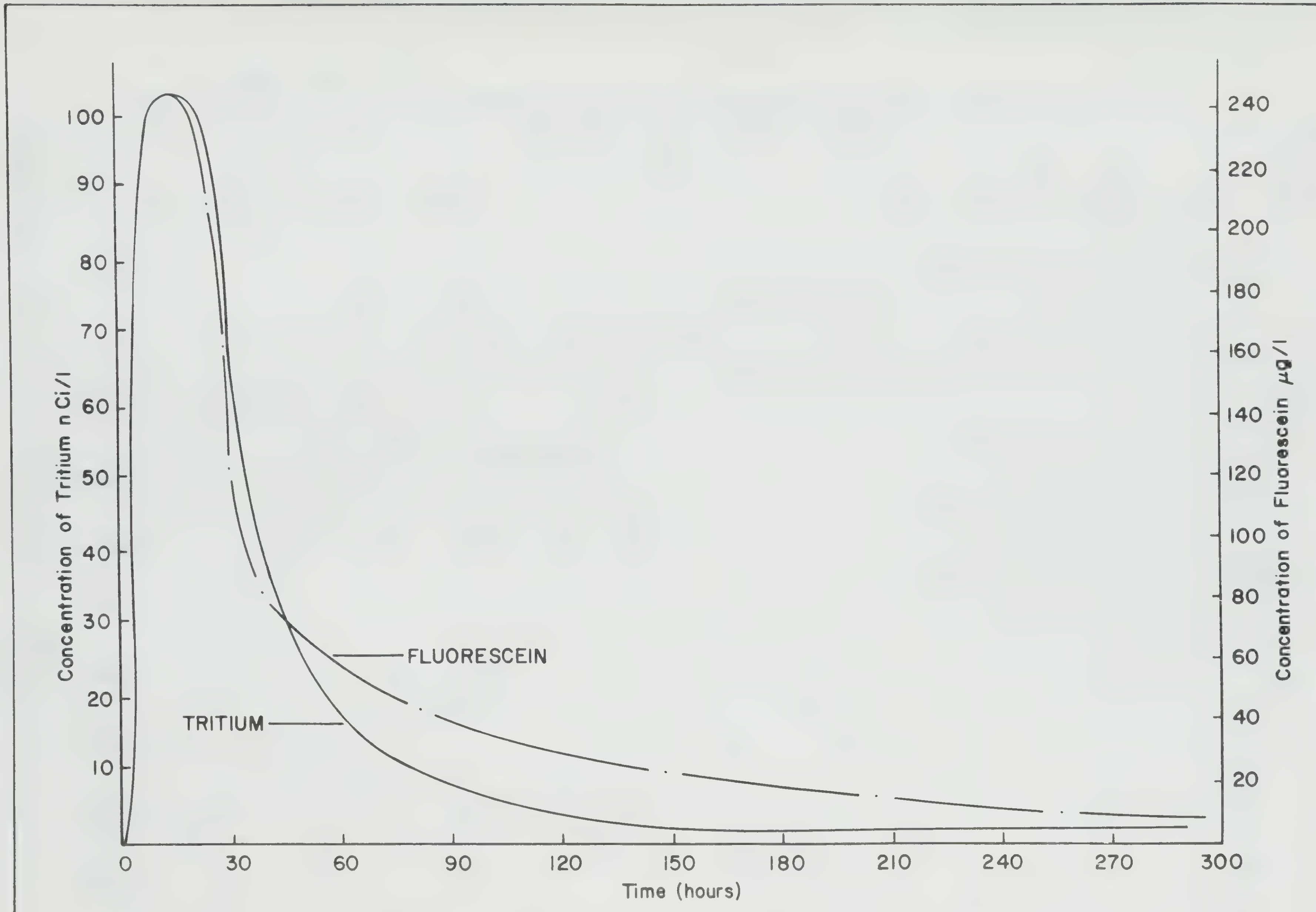

FIG. 5. EFFECT OF TIME ON CONCENTRATION OF TRACERS IN EFFLUENT FROM SAND FILTERS (Whitby - sand filter 3)

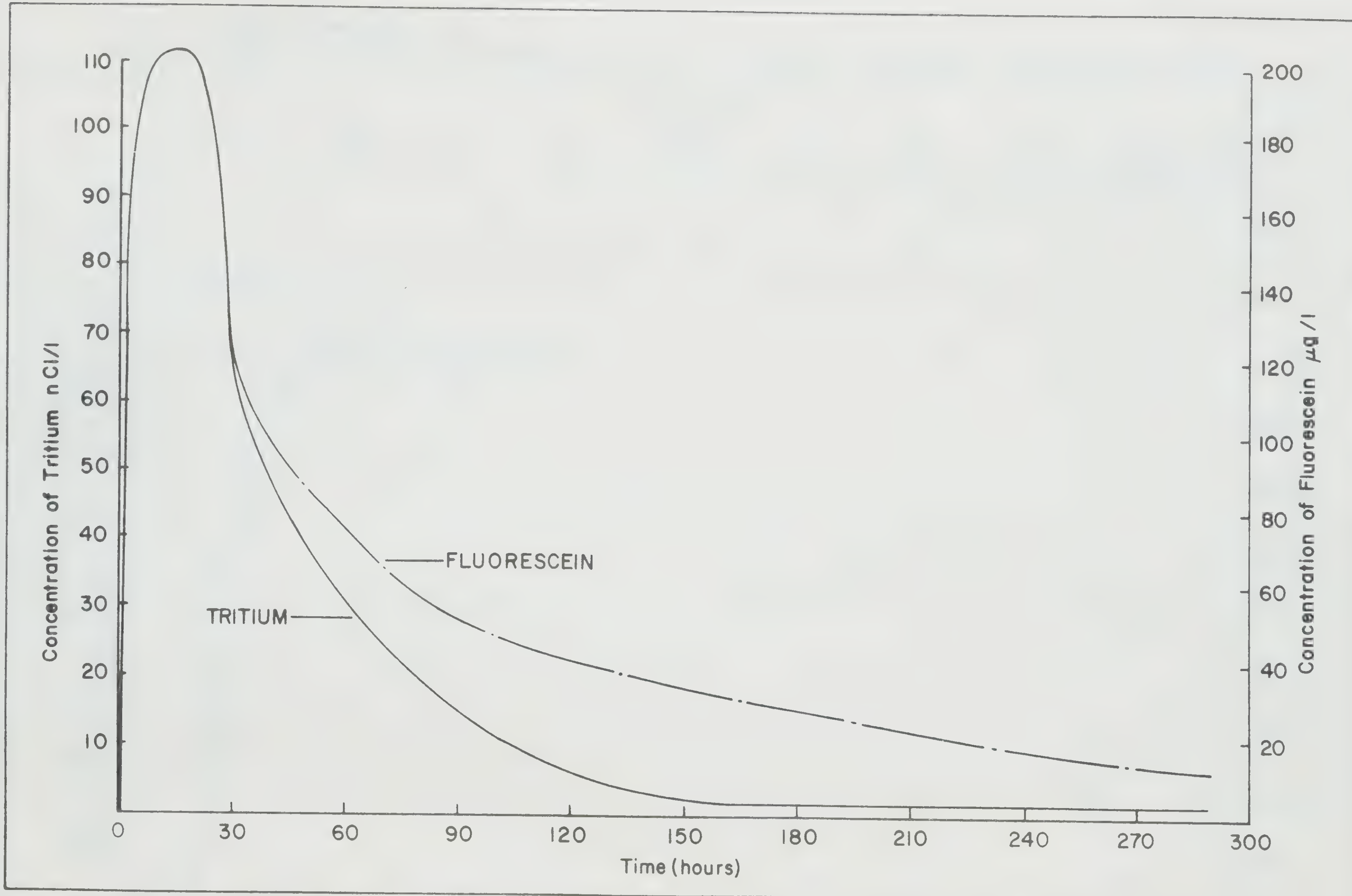

FIG. 6. EFFECT OF TIME ON CONCENTRATION OF TRACERS IN EFFLUENT FROM SAND FILTERS
(Whitby - sand filter 6)

6. Discussion

The "blind hole" techniques applied in the 1972 part of this study simulates to a great extend the flow pattern taking place in a conventional leaching bed system. It is, however, important to follow also the same pattern of hydraulic loading as it is usually applied in the sewage disposal systems, i.e. to maintain a long lasting trickling load. Unfortunately in the 1972 study the tritium was introduced into the blind hole only once and then only flushed once with water in order to push the tracer towards the ground water. The subsequent vertical movement of the tritium through the unsaturated soil was caused by occasional rain fall and that was probably the main reason why the observed velocity of the vertical movement of the tritium was only 0.04 m/day. In an-other study (Ref. 4, Part 2) where the leaching bed was loaded continuously with domestic sewage, used as the transporting medium for the tritium, the velocity of the vertical movement of the tritium in the unsaturated soil was 0.18 m/day.

The velocity of the horizontal underground movement of the tritium was determined in the 1974 study with a considerable accuracy (± 1.3%). However when the distances between the well points were relatively small (1972 study) better accuracy in determination of the velocity required more frequent sampling for tritium (once or twice daily) in order to fix more accurately the time at which the tritium reached the well points.

When studying the velocity of the underground movement of tracers only the movement in the direction of maximum slope of the water table was determined. However, some lateral movement of tritium was also observed. It would be of practical use to

study also the lateral movement of the tracers.

It was assumed throughout the study that tritium used in a form of tritiated water must move with the same velocity as the ground water in which the tritium was diluted.

It was of practical interest to compare the velocity of ground water flow determined by using tritium with the velocity calculated from the measured soil permeability coefficient and measured on-site hydraulic gradient.

In the 1974 study, the average velocity of movement of tritium, presumably the same as that of the ground water flow, was 0.61 m/day. The average permeability coefficient, k, of the soil obtained from the field and laboratory measurements was 0.7×10^{-7} cm/sec, and the hydraulic gradient, i, of the ground water was about 4%.

According to Darcy's Law the seepage velocity, V_S, is equal to the product of the permeability coefficient - k and the determined hydraulic gradient - i, divided by the porosity of the soil $V_S = Ki/n$.

In this study, $k = 0.7 \times 10^{-7}$ cm/sec, $i = 0.04$ and $n = 40\%$ thus $V_S = 0.6 \times 10^{-5}$ m/day.

The velocity of the ground water determined by using tritium was 100,000 times greater than the velocity calculated by using Darcy's Law.

These data point out the difficulties in obtaining direct correlation between soil permeability and water flow velocities, particularly in cohesive soils.

The lack of correlation is, to a great degree, attributable to the respective test conditions:

Field Permeability Test

Piezometers are used in this test. During the driving of the piezometer into the ground the porous cylindrical surface of the device is smeared by the relatively impervious, clayey soil, thus the rate of outflow of the water from the piezometer is considerably reduced. Again, the process of driving the piezometer may also cause closing of the cracks and fissures which exist in natural undisturbed soil and which normally permit easier passage of water through the soil.

Laboratory Permeability Test

A small cylindrical sample is used in this test (diameter-5 cm, length - 7.6 cm). The procedure of taking the sample by driving a thin-walled Shelby tube into the subsoil and the consolidation of the sample prior to the permeability test may cause closing of the natural cracks and fissures in the sample, thus reducing considerably the rate of water flow during the laboratory test.

7. Summary & Conclusions

7.1 Methods Used

Two methods of studying the movement of tracers through soil were applied:

a. The "blind hole" method where the tracers in a liquid form were introduced into a hole drilled in the ground to a depth of one metre above the water table. The tracers were picked up later from well points drilled downstream from the blind hole.

b. A method of injecting tracers directly into the ground water and intercepting the tracers in well points drilled downstream from the injection point.
Both of the methods (a and b) proved to be suitable for studying the movement of tracers through soil; however, when method "a" is used the tracer must be injected into the blind hole continuously for a period of about 5 to 10 days.

c. The movement of tracers through sand filters was studied by introducing the tracers into the septic tank effluent being treated by the filters. This method also proved to be suitable for studying the movement of tracers and septic tank effluent through sand.

7.2 Movement of Tritium

a. Tritium was found to be an excellent tracer for tracing the subsurface movement of septic tank effluent.

b. Tritium was detected in well points located at distances

as far as 65.0 metres from the source of the tracer.

c. In soil containing 74 to 95% silt and clay, the velocity of movement of tritium in the saturated portion of the soil, assumed to be the same as that of the ground water velocity, was found to be 0.50 m/day.

d. The velocity of the vertical movement of tritium through the unsaturated portion of soil, was 0.04 m/day, i.e. about 10 times less than that in the horizontal direction. The velocity in the vertical direction was determined by calculations based on distances and times measured. The calculated velocity of vertical movement of tritium is low in comparison with the velocity - 0.18 m/day of the vertical movement of septic tank effluent entering the absorption trenches continuously (4).

7.3 Vertical Movement of Tracers through Sand Filters

a. The velocity of the vertical movement of tracers (tritium, fluorescein and rhodamine B), through sand filters was found to depend strongly on the grain size of the sand used. The vertical velocity of all the tracers was 7.1 m/day when sand of a grain size D_{10} = 0.24 mm and uniformity coefficient C_u = 2.8 was used and as great as 16.8 m/day when the grain size was D_{10} = 2.5 mm and uniformity coefficient C_u = 1.2.

7.4 Movement of Fluorescein

a. In undisturbed soil containing between 74 to 95% clay and silt the fluorescein moved only a distance of 1.5 metres from the injection point. Fluorescein moved

vertically through sand filters with the same velocity as tritium (7.1 to 16.8 m/day). Generally, fluorescein was found to be suitable for tracing the movement of effluent through sand but not suitable for use in undisturbed soil containing clay and silt.

7.5 Movement of Phosphorus through Soil

In undisturbed soil containing 74 to 95% clay and silt the movement of phosphorus appeared to be extremely limited in range and velocity. The distance from the injection point to the point where phosphorus was detected in the ground water was not greater than 1.75 metres and the average velocity of movement was 0.07 m/day. The limited distance and velocity can be attributed to phosphorus retention in soil.

7.6 General Pattern of Movement of Tracers through Soil

a. At a given point in the ground water, a change in concentration of tracers with time was observed. After a rapid increase in concentration and after reaching a peak value the concentration dropped gradually with time. The general pattern of the change in concentration with time followed Gumbel's standard skewed distribution curve.

b. Finger-like flow of tracers and short circuiting of the tracers in the ground seems to be the reason why some well points, located in the path of the movement of the tagged ground water, were bypassed by the moving tracers.

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